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INTELLIGENT SYSTEM APPLICATIONS TO PROTECTIONS, CONTROL AND MONITORING WITHIN SUBSTATIONS

by

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INTRODUCTION

This paper reports some of the results of CIGRE Working Group (WG) 34-07. This WG was formed in 1991 with an assignment to investigate trends and recommendations related to the substation control and protection equipment design. The results of the study of the use of intelligent techniques in substation protection, control and monitoring are reported in this paper.

KEYWORDS

Intelligent System - Protection - Control - Monitoring - Substation

1. SURVEY OF PREVIOUS ACTIVITIES

Application of intelligent techniques to power systems started with the use of expert systems in security assessment, power system restoration, fault section estimation and real-time processing of fault waveforms. A number of other applications in the area of planning, monitoring, control and protection were reported so far.

The CIGRE activity in this area has been initiated in late 1980 and several reports have been generated [1],[2]. The IEEE activity has also been reported through different publications [3],[4]. Some further activities are being carried out in the various CIGRE Study Committees and the following Committees of the IEEE Power Engineering Society : Energy Development and Power Generation, Power System Engineering, Power System Relaying, and Transmission and Distribution.

Very few reports were generated so far summarizing the use of expert systems for the substation protective relaying and related functions [4],[5]. This paper summarizes the trends and gives recommendations for future uses of intelligent techniques based on the experiences reported so far.

2. REVIEW OF INTELLIGENT SYSTEM TECHNIQUES

Nowadays a definition of an Intelligent System can be given as a set of various hybrid programming techniques which are well suited individually to represent and to solve a specific part of a problem and adjusted to reach the best conclusions. Some of these intelligent techniques known today are discussed below.

2.1 Expert Systems

In such systems, the knowledge takes the form of rules written using a "If... Then..." syntax, and facts that generally describe the domain and the state of the problem to be solved. A generic inference engine uses the facts and the rules to deduce new facts which allow the firing of other rules. This process continues until the base of facts is saturated and a conclusion has been reached. The forward and/or backward mechanisms can be used to fire the rules and to deduce the conclusions. Rules based systems represent still the majority of the existing expert systems. In the late eighties a second generation of expert systems was introduced. These combine heuristic and "deep" knowledge based on models of the operation of the system or the reasoning structure.

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2.2 Neural Networks

A Neural Network is a set of elementary neurons which are connected together in different architectures organized in layers. An elementary neuron can be seen like a processor which makes a simple non linear operation on inputs producing a single output. A weight is attached to each neuron and the training stage consists of adjusting different weights according to the training set. Neural Networks are attractive techniques because they do not require tedious knowledge acquisition, representation and writing stages. The speed of processing, allowing real time applications, is also an advantage.

2.3 Fuzzy logic

Fuzzy logic is a mathematical technique suitable for dealing with imprecise data and problems that have many solutions rather than one. Fuzzy logic can deal with values between 0 and 1, and approximate reasoning through the ranges of data instead of crisp values. In the fuzzy logic systems, the knowledge is represented by facts and rules which are expressed in terms of "vague" words such as uncertain, certain, small, medium, large etc. A fuzzy inference program uses this qualitative knowledge to deduce the conclusion which have the highest possibility to occur.

3. EXISTING AND POTENTIAL APPLICATION AREAS

In considering the use of intelligent systems for substations monitoring, control and protection, one may divide the applications into :

- individual device level,
- substation level.

Detail reference list for the examples discussed below will be given in the WG 34-07 final report.

3.1 Individual device level

Most of the intelligent system applications in relaying are aimed at improving the conventional relaying functions. However, some new approaches were also introduced. The main contributions are provided for the following applications :

- adaptive relaying and reclosing,
- improved fault location,
- high impedance fault detection,
- improved power transformer protection,
- new transmission line relaying principles.

Table I summarizes some examples of the most recent applications.

Table I. Individual device level applications

Application area	Improvements	Intelligent Technique used
Distance Relaying and Related Functions	Fault type Identification	Fuzzy Sets
	Fault detection discrimination	Neural Nets
	Adaptive protection of double-circuit lines	Neural Nets
	Adaptive selection of the operating characteristic	Pattern Recognition
	Adaptive reclosing	Neural Nets
Fault Location	Analysis of the disturbance pattern	Neural Nets
High Impedance Fault Detection	Detection of the faults	Neural Nets
Power Transformer Protection	Selectivity between faults and operating conditions	Fuzzy Sets
Transmission Line Relaying	V-I vs R-X plane for fault detection and classification	Neural Nets

Table II. Substation Level Solutions

Application Area	Improvement	Intelligent Techniques Used
Sequence of Events (SOE) Recorders	• Automated analysis • Consistency check through redundancy	Rule based expert systems
Digital Protection Relays (DPR)	• Analysis of relay operation • Analysis of faults	Expert Systems (not yet reported)
Digital Fault Recorders (DFRs)	• Automated analysis • Combining of analog and contact information for redundancy check	Hybrid Solution, Signal Processing and Rule Based Expert System

3.2 Substation level

At the substation level, most of the applications available today refer to the fault analysis. A summary of the possible approaches is given in table II. Some approaches to improved bus bar protection have also been reported. These applications are discussed below.

3.2.1 Fault monitoring and analysis

Up to now, all the analyses of network faults were done manually by analyzing a posteriori all the recordings of analog or logic (contact) data related to the HV gear as well as the protection and control systems. Since there is a large amount of data to be processed, the manual techniques are not practical and they require significant time to complete. Automating the analysis process can produce the results much faster and can be of significant practical value to the operators.

Two categories of automatic fault analysis systems reported so far may include : those which are fed by the time tagged sequence of events (SOE) generated during disturbances and those fed by the sampled values of the analog wave forms of currents and voltages as well as contacts generated during disturbances and registered by digital fault recorders (DFRs).

a) Fault analysis using SOE recorders

These systems are fed by the events which are time tagged and recorded at the substation level [6]. The states of breakers and the tripping orders are the minimum information for making a diagnosis. To make analysis more powerful, the detailed sequence of events generated by the protective relays, (starting, phase selection, directional, zone, teleprotection, closing signals etc.) fault locators and autoreclosers are very useful. To improve the diagnosis, data coming from neighboring substations like teleprotection signal may sometimes be helpful. The precision of the time tagging is another important factor for the accuracy of the diagnosis.

Analysis of the behavior of the protection system may include the verification of the correct operation of the protective equipment inside a substation, the loss of selectivity detection and the measure of the clearance time. This may be essential for performance evaluation and preventive maintenance purposes.

b) Fault analysis using DFRs

A common practice in a number of countries is to use digital fault recorders (DFR), quite often also called Disturbance Recorders, Transient Recorders, etc. These devices are an advanced version of the "old" designs of an analog device called Strip Chart Recorder or Oscilloperturbograph. The role of these devices is to record analog waveforms and contact (status) information in substations. This data is then used by the operators in analyzing events that have caused the disturbances.

One of the main practical problems with the use of the recorders is handling of the large amount of data being recorded. Most of these instruments have as many as 64 analog and 125 contact inputs. All the input data is recorded each time the recorder is triggered. This results in the recordings of some data that may not be relevant for the analysis since, in many cases, only a limited number of inputs are affected by a given disturbance.

In the case of a digital recorder design, a number of different expert system approaches may be used to facilitate the automated processing of the recorded data [7],[8].

3.2.2 Bus bar protection

One of the recent papers is also discussing use of neural networks to improve bus-bar protection. The neural network is utilized for pre-processing the data for the purposes of restoring the distorted signals occurring due to the saturation effects of current transformers.

4. FUTURE TRENDS AND OPPORTUNITIES

4.1 New designs of individual devices utilizing intelligent solutions

Typical examples of the new applications in the substations are fault diagnosis and high impedance fault detection. It may be argued that these applications are not indeed new since they have been discussed for the last 20 years. On the other hand, it is well known that there were no standard solutions introduced in the past to successfully deal with these problems. Only the recent implementation attempts have demonstrated that working solutions can be developed using intelligent systems.

In the case of the fault diagnosis, it is important to combine information derived from both analog measurements and contact indications to be able to make a conclusion about a fault event and an operation of the related equipment. The use of expert systems have been quite useful when a large number of comparisons had to be performed based on a number of different parameters. Implementing the same application using an algorithmic approach may be inconvenient, if not impossible, due to the heuristic nature of the diagnostic search procedures.

In the case of the high impedance fault detection, it is important to recognize patterns of waveforms for different types of conditions (level of loading, type of soil, type of fault). In most of these cases, the fundamental frequency signal does not indicate a major change, while most of the information needed to distinguish these events from some other normal operations is contained in the higher harmonics. The use of signal processing techniques shows the processing complexity to be the major disadvantage. This, in turn, requires more powerful microprocessors and more complex software. Recently, it has been demonstrated that the application of neural networks may be an appropriate approach to this problem since it can be defined as a pattern recognition problem. The neural network processing applied to this problem eliminates a need to define complex thresholds for various signal parameters obtained using known signal processing techniques.

4.2 New designs of substation integrated/ coordinated systems utilizing intelligent solutions

In a context of all digital secondary equipment available in substation, it is expected that the integrated/coordinated protection and control equipment will give more data. In these conditions, intelligent systems could avoid the bottleneck of data transmission links by combining the analysis of the digital fault and the sequential event recordings as well as recordings available from digital relays.

A hierarchical fault diagnostic system can be imagined in the future. An accurate fault recognition and location are possible at the substation for all the faults which are located inside the substation or on the lines fed by the substation. A full integrated protection and control system makes easier the implementation of such a system. This hierarchical solution is illustrated in figure 1 :

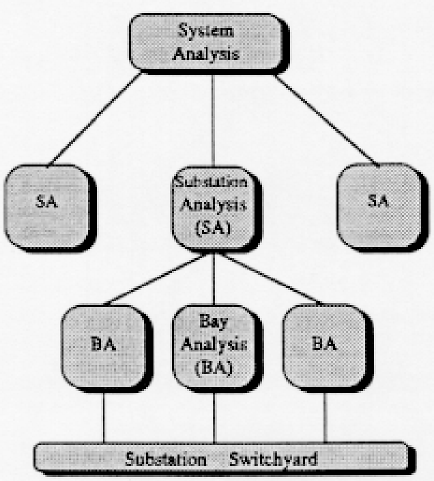

Figure 1: Hierarchical Automated Fault Analysis

At the bay level, information generated by the protections (main and backup), the fault locators and the reclosers are considered. Comparing the behavior of these devices, a mini synthesis can be performed at this first level. The substation is the second level of synthesis. Taking into account all the feeders of the substation, the diagnosis can be reinforced and sent to the district or regional control center.

5. IMPLEMENTATION ISSUES AND RECOMMENDATIONS

5.1 Data requirements

The following discussion will be concentrating on one aspect of this problem, which is probably the most interesting one. This is the possibility to utilize the excess data to make more comprehensive conclusions about overall substation equipment operation than what is available today through the SCADA systems.

The data types usually include samples of voltages and currents on the lines and buses as well as contact status from the switching equipment. The analysis shows that this data is redundant since there exists a relationship between the analog quantities in a given substation and the switching equipment open/close state. This property can be explored only if the data from various equipment in the substation is brought to a common database so that the redundancy can be explored. In this case, various intelligent system approaches can be utilized for a specific type of processing that will directly explore the properties of such a database.

Another important issue for the intelligent system applications in the substation is the temporal element. This consideration relates any data sample to any other one using a well defined time scale. The advantage of the substation data is that it can be used to determine sequence of events using the fundamental frequency sinusoidal waveform as a time reference. In order to preserve this as a reference, all the data needs to be sampled synchronously. This introduces an additional requirement that some sort of sampling synchronization exits between all the equipment in a substation. The use of standard absolute time signal as a reference may be the most beneficial approach known.

Finally, if the substation data is to be combined and/or consolidated for the purpose of implementing some intelligent processing techniques, it is also important to provide consistent accuracy for all the measurements. This requirement may mean that all the substation equipment uses the same accuracy for the front end electronic aimed at signal sampling and conversion into a data base. A standardization effort in this area would be desirable.

Analysis of the new, all digital, solutions for the substation equipment shows that the main trend is to provide a large amount of data related to the substation quantities. The analysis of data available from typical modern digital relays shows that the quantity of data recorded by a relay after a fault may very well be in excess of 20 k Bytes. It can be noticed that an increase of the sampling rate is also expected in the next few years. If all this data is stored after it is used for the main application, it becomes available for any subsequent processing. The fact that this date is available opens a question of what to do whit it. Furthermore, the question may be extended to include the issue of the use of intelligent systems to compress the data or to make some additional conclusions based on this data.

5.2 Knowledge acquisition, validation and testing

In a digital substation, special care is needed for the description of the substation configuration. Most of the time manufacturers use a special tool dedicated for this purpose : the names of the bays, devices, · and description of the behavior of some automatic devices using a special language based on block diagrams, Grafcet or Petri Nets. Intelligent system applications do require their own databases that can be derived from the substation general data base.

Validating an intelligent system software is another important factor that has to be considered. This factor comes from the development method commonly followed, based on the use of a prototype. This implies that part of the knowledge is acquired in a iterative process in which the results of test are fed back to the intelligent system functional specification. This, in turn, implies that a complete, consistent and accurate specification of the software is not available at the beginning of process, in contrast with most of conventional software developments.

Many intelligent applications in the field of power system have been developed by the power engineers. This is generally considered an advantage that may speed up the knowledge acquisition process. On the other hand, a power system engineer could be less familiar in intelligent system programming techniques than a specialist, which can lead to the absence of a systematic application of the methods, procedures and rules of software design and the subsequent difficulty in validating intelligent system software.

It is very important to choose a good strategy for testing. Test should be carried out by persons not involved in the development of the system. To include some end-user in the testing team could help in pointing out problems and weaknesses of the software not noticed by developers.

The most common and probably the most effective approach is to combine modular and global testing. After exhaustive testing of each module, tests of combinations of modules, of complete subsystems and the interfaces among them have to be done, and if it is possible of the whole system itself.

Another possibility is the use of simulators that in many cases cannot be easily developed. An accurate simulation would permit to establish the functional requirements more consistently.

5.3 Maintenance and Upgrades

The use of intelligent systems requires careful consideration of the maintenance and upgrades techniques and practices. It is not only important that the general rules such as modularity, simplicity and consistency are followed but also some considerations peculiar to the intelligent techniques need to be fully understood and appreciated.

The expert system solutions may require a special user interface for upgrading the rules and knowledge base. Possibility for adding the rules and expanding the knowledge base in an easy way is the main requirement.

The use of neural nets is heavily dependent on the training capability available to tune the given network to the selected application. Elaborate tools for simulation of power network conditions for the purpose of neural net training may be required to enable efficient use of neural net techniques.

The fuzzy logic applications may also require some special care when acquiring and classifying application data uses for definition of the fuzzy variables. Future upgrades may require additional application data and its classification in order to decide if the level of imprecision has changed.

Since very few practical applications of intelligent systems are available in the substation today, the issue of maintaining and upgrading will have to be evaluated further once extensive practical experiences are available in the future.

6. CONCLUSION

Based on the discussion given in the paper, the following can be concluded :

- Present intelligent system applications within substations seem to include both individual device and system implementations.

- The most promising application are in the area of new solutions such a as high impedance fault detection and hierarchical automated fault analysis.

- A number of implementation issues such as data requirement, knowledge acquisition, validation and testing, as well as maintaining and upgrading are indeed critical and need careful consideration.

7. BIBLIOGRAPHY

[1] C.C.Liu, et. al., "Practical Use of Expert System in Planning and Operation of Power Systems," (*Final Report, CIGRE Task Force 38-06-03*, September 1992).

[2] CIGRE Task Force 38.06.04, "A Survey of Expert Systems for Power System Restoration," (*Electra*, No. 150, October 1993).

[3] A Tutorial Course Text, "Knowledge-Based System Techniques with Applications to Power Systems," (*IEEE Publication # 93 EHO 387-1-PWRD*, October 1993).

[4] IEEE Power System Relaying Committee, Working Group D-10 Report, "Potential Applications of Expert Systems to Power System Protection," (*IEEE Transactions on Power Delivery*, Vol. 9, No. 2, April 1994).

[5] M.Kezunovic, et. al., "Expert System Applications to Protection Substation Control and Related Monitoring Functions," (*Electric Power Systems Research Journal*, Vol. 21, pp. 71-86, April 1991).

[6] P.Fauquembergue et al., "Monitoring of Protection System Behavior using an Expert System which Analyses Substations Sequential Events Recordings - Field Experience at Electricité De France," (*Proceeding of the IEE*, York, April 1993).

[7] M.Kezunovic, et al., "Expert System Reasoning Streamlines Disturbance Analysis," (*IEEE Computer Applications in Power*, Vol. 7, No. 2, April 1994).

[8] L.Cederblad, et. al., "A Knowledge based System for Automatic Evaluation of Disturbance Recordings," (*Texas A&M Relay Conference*, College Station, Texas, April 1993).

RESUME

Ce rapport présente quelques résultats du Groupe de Travail CIGRE 34-07 qui traite entre autres de l'utilisation de techniques intelligentes pour les systèmes de protection, de conduite et de surveillance des postes électriques. Les techniques intelligentes dont il est question dans ce rapport concernent aussi bien les systèmes experts que les réseaux de neurones ou encore les systèmes à logique floue.

Bien qu'il n'y ait que très peu de rapports décrivant l'utilisation de ces techniques dans les systèmes de protection et fonctions associées, on peut considérer qu'il existe aujourd'hui des applications au niveau de l'équipement lui-même ainsi qu'au niveau du poste.

Au niveau de l'équipement, les principales applications recensées concernent les fonctions de relayage et de réenclenchement adaptatifs, l'amélioration de la fonction de localisation de défaut, la détection des défauts de très forte impédance, l'amélioration de la protection de transformateur de puissance ainsi que des nouveaux principes de protection de ligne de transport.

Au niveau du poste, la plupart des applications disponibles aujourd'hui se rapportent à l'analyse de défaut. On note qu'il existe, d'une part les systèmes d'analyse à partir des données issues des consignateurs d'états et, d'autre part, les systèmes d'analyse à partir des perturbographes numériques. On recense aussi des approches utilisant des techniques intelligentes pour améliorer la fonction de protection de barres.

Dans les nouvelles conceptions de matériel de contrôle-commande de poste, il est nécessaire de tenir compte de l'apport des techniques intelligentes. Celles-ci offrent en effet des solutions tout à fait adaptées en particulier dans le domaine de la reconnaisssance de formes d'onde ou d'identification de grilles de solutions ainsi que pour faire la synthèse des données toujours plus nombreuses générées par le matériel de protection et de contrôle-commande.

Mais si l'on veut tirer pleinement profit de l'utilisation des techniques intelligentes, il est important que les applications puissent accéder à toutes les données générées par l'ensemble du matériel de contrôle commande du poste et que ces donnéees soient de bonne qualité en particulier en terme de datation et de synchronisation. Par ailleurs, dans l'élaboration d'une application intelligente, le plus grand soin doit être apporté aux phases de modélisation des connaissances et de validation. Enfin pour satisfaire les besoins d'évolutivité et de maintenabilité, il est vivement recommandé d'utiliser des méthodes structurées dans tout le cycle de vie de l'application.